Fiber Optic Design and Applications

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PREFACE

The field of fiber optics is in its infancy; the technology is only 15 years old. Copper transmission line technology is relatively old and well developed. Many new and innovative applications are in store for fiber optics in the next 15 years. Telephone companies such as Bell and GTE are experimenting with fiber optic trunks; these companies are known to be conservative in their research efforts. The medical field is also keenly interested in instrumentation applications; they have been one of the pioneers in the technology. Fiber optics is a broad field; it will have applications in communications, the transducer field, the medical field, guidance systems, and servo systems, just to name a few.

The purpose of this book is to acquaint its audience with the fundamental properties of fiber optics. Numerical examples will be presented in most chapters to reinforce the readers knowledge of the subject matter. Several of the circuits in the text are authentic working models, but these designs are only meant as a benchmark to help the readers who wish to experiment and get familiar with the technology quickly. This book would be an excellent reference text for senior level engineering students or an engineer desiring to gain knowledge of the fundamentals. Transmitter and receiver design projects with signal processing would be excellent to assign as research.

The book is organized in a useful manner; the introduction in each chapter has a brief summary of the chapter. Anyone desiring to gain a superficial knowledge of the subject can do so easily. The latter part of each chapter will be devoted to the design aspects of the subject.

The book is intended for an audience with an adequate background in mathematics (differential equations). To understand some of the finer points of design, the reader should have a fundamental knowledge of circuit analysis and digital logic.

A bibliography following each chapter (but the first) provides reference articles and books for further reading. The author plans a second volume in the future to cover integrated fiber optics, which is in the research stage at present.

The chapters are written in a logical order to cover the subject matter with the most effect. The progression of the book is from components to systems study, with economic and future outlook at the end. However, these latter two subjects are not by any means insignificant.

A brief overview will give the reader the high points of the text. Chapter 1 is a summary of the historical events that encouraged research in fiber optics. This chapter will answer the two fundamental questions. What is fiber optics? Do fiber optics offer any advantages over conventional copper cable technology?

Chapter 2 addresses the study of fiber optic waveguides. A comparison of copper and fiber optic cable is made, with the advantages and disadvantages of each. This chapter provides the reader with an analysis of waveguides as applied to fiber optics. Conventional ray theory is used to describe the waveguide parameters and their behavior. To make the study complete, field theory analysis is also presented. The properties of waveguides that cause signal corruption are discussed at length. Radiation effects are addressed, in particular nuclear radiation, which is of prime importance. A table of commercially available fiber optic cable is provided with their parameters to allow the reader to examine these sources. Methods of testing the cable will complete the chapter. The reader is led through some sample design problems, when appropriate.

Chapter 3 is a preliminary examination of semiconductor LEDs and lasers to determine their properties and construction. The discussion is meant to acquaint the audience with available sources; this section is not covered with a great deal of mathematical rigor. The reader cannot modify the source parameters to any extent; only manufacturers can affect source parameters. The chapter concludes with a discussion of nonsemiconductor lasers, such as YAGs, fluidic, and gas lasers; these latter devices are not covered in any great detail.

Chapter 4 delves into the drive circuitry for lasers and LEDs. The chapter contains the design equations necessary to implement transmitter circuitry. Linear analog driver design is addressed with compensation techniques. Several circuits are provided as examples of driver design for both linear and digital circuits. Transmitter circuits with encoding to provide self-clocked waveforms are discussed in detail, with digital circuit diagrams. The discussion then moves on to encryption techniques and CRC checking. A discussion of commercially available transmitters follows; the specifications of these devices are covered in detail.

Optical detector physics is covered in Chapter 5. Emphasis is on the PIN and APD diodes, with an introduction to phototransistors. Mathematical rigor is not presented in this chapter; however, some electronic models for these devices are addressed.

Chapter 6 examines fiber optic receivers from a design point of view with a large number of receiver example circuits. Models of complete circuits with sources included are developed. The chapter delves into the design of decoding circuitry and methods of designing wideband receivers. A table of commercially available receivers is discussed, with emphasis on the development of receiver specifications.

Chapter 7 is dedicated to the study of connectors and splicing techniques with all the associated problems. The discussion centers on the techniques various manufacturers use for termination, with a table of current manufacturers. The reader is assisted in making choices from the table based on system requirements. Splicing techniques have a variety of approaches; some are rather complex and expensive, while others are simple and inexpensive. Splice techniques with diagrams are provided to acquaint the reader with the more common types. A comparison and discussion of the various commercially available items will assist the reader to become quickly aquainted with them.

Chapter 8 provides an introduction to components particularly useful in star networks, the components referred to as couplers. A great variety of these devices are available commercially. An analysis of several of these components assists in formulation of specifications for them. Systems applications are discussed to a great extent. Fiber optic switches are also a topic of this chapter, a subject that is covered in detail due to its great importance. LANs networks are one large application for these devices. Some switches are available commercially, while others are not. Some important analysis is also presented that is usually ignored in most texts. Test and measurement methods and examples are in the latter sections to make the chapter complete.

Chapter 9 is very important as it integrates the knowledge gained in the first eight chapters into a system. Several fiber optic systems are designed and analyzed for their advantages and disadvantages. A discussion of systems limitations is presented here, such as bandwidth, attenuation, and dispersion. Worst-case systems will be formulated with pessimistic design examples provided for the reader. Several complete systems designs are presented, complete with system and component specifications.

Chapter 10 addresses application to local area networks (LANs), owing to their vast importance and rapid growth. The types of networks discussed are the basic ring star and bus; variations of these, the token ring, slotted ring, and bus/ring combination, are also examined. One of the most popular LAN techniques at this time, CD/CSMA (carrier detect/ carier sensed multiple access), is discussed in detail, owing to the commercially available monolithic controller integrated circuits. CATV applications are also covered. The final topic is transducers and their application to instrumentation and feedback systems.

Chapter 11 covers economic considerations with a study of plant costs. A comparison of fiber optic and copper cost factors is made on a previously designed system. Estimates of component costs and their trends in the present market are addressed here. Future projections can be made on component cost.

The future outlook is discussed in Chapter 12, with a digression on the future of fiber optics technology. The trends of industry to move toward monomode waveguides in the future is addressed here. Some of the breakthroughs in the communications industry are investigated, with likely future advances.

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CONTENTS

chapter 1

INTRODUCTION

When data are transmitted over an optical waveguide, it is considered fiber optic transmission. The most common optical waveguide materials are plastic or glass. Extremely high purity materials are required for the manufacture of these waveguides. Dopants are added to enhance certain waveguide properties. If, for example, ordinary window glass were made into a waveguide, the maximum transmission distance would be less than 1 foot. Material purity was a major problem during the early efforts to manufacture fiber optic waveguides; the present process is a vast improvement.

HISTORICAL EVENTS LEADING TO PRESENT-DAY FIBER OPTICS

Optical waveguide phenomena are not a recent discovery. A historical experiment was conducted at the Royal Society in England by John Tyndall to demonstrate the light waveguide phenomenon. The experiment consisted of a vessel filled with water and illuminated with light. When a stream of water was allowed to flow from the vessel through a hole, light was conducted along the path of the stream. This experiment was conducted in 1854 and it is one of the first recorded. However, it was not until the 1950s that optical waveguides were put to a more practical use in the fiberscope. These devices were designed with glass waveguide bundles to transmit images. Transmission distances were short due to the high loss exhibited by these early waveguides. Losses were in the thousands of decibels per kilometer (dB/km). These waveguides were unacceptable for communication networks, owing to this high attenuation. Research continued, the next important breakthrough occurring in 1966 with the famous paper written by K. C. Kao and G. A. Hockham, "Dielectric-fiber surface waveguides for optical frequencies," *Proc. IEE* (London) 113, 1151–1158 (1966), reference [1], which examined the properties of glass employed in optical waveguides. The paper advanced the theory that impurities in glass, in particular, metallic ions, were responsible for the high attenuation. Research soon confirmed the findings of the paper. Two years later a discovery was made of how modal dispersion could be reduced through grading the index of refraction of the glass. This discovery made possible increases in transmission bandwidths.

Owing to the improvement in waveguide properties, communication equipment manufacturers began to look favorably at optical waveguides as a transmission medium. The upper limit on attenuation of 20 dB/km was the communication industry goal; the limit was soon surpassed by Corning Glass with a monomode waveguide. At this point, a flurry of research began for further breakthroughs in lowering attenuation and extending transmission bandwidths. A capillary tube filled with a liquid medium produced waveguides with losses of less than 10 dB/km. In 1972, Corning Glass fabricated a multimode waveguide with a minimum loss of 4 dB/km; today these figures are lower. The trend of industry is toward monomode waveguides (a monomode waveguide will only support single-wavelength transmission; refer to Chapter 2). Monomode waveguides have lower loss and larger transmission bandwidths. Attenuation of 0.2 dB/km has recently been achieved in monomode waveguides at a wavelength of 1.55 micrometers (μm). Theoretically, the optimum transmission wavelength is 1.27 μm, where material dispersion is zero. Termination problems need to be addressed before monomode waveguides will be widely accepted.

In parallel with waveguide research, new sources for fiber optic transmission were being investigated. The Burrus diode and the heterostructure diode (DHS) are the two most notable breakthroughs in light-emitting diode (LED) research. Laser sources reliable enough for data communication transmission were not available until 1979, when source life was increased to 100,000 hours. LED sources with wavelengths in the 800-nanometer (nm) range are the most popular at present, due to their low cost and ease of manufacture. Research effort is now directed toward the longer wavelength LEDs because of the lower dispersion loss at 1270 nm.

Fiber optic technology is in its infancy. Research will bring many breakthroughs in the next decade. At present, low-cost splicing and terminating techniques are needed for monomode waveguides. These areas are where the breakthroughs will most likely take place. Splicing or terminating monomode waveguides requires extreme precision alignment. Terminations with fiber optic connectors have losses of 0.1 dB with liquid couplant and 1.5 dB with dry connections. Connectors are a source of research effort, with only de facto standards emerging.

FIBER OPTIC COMMERCIAL APPLICATIONS

A prime area for fiber optic technology is local area networks, commonly referred to as LANs. Communication distances of less than 10 kilometers (km) fall into this category. LANs networks can interconnect office machines, components of a distributed computer system, machine tools, and so on. Several standards and manufacturer de facto standards are emerging. This material is given more comprehensive coverage in Chapter 8. Both broadband and baseband transmission techniques are popular with LANs designers. Each network has variations in codes and protocols.

Fiber optic transmission is more adaptable to baseband than broadband networks owing to the nonlinearities in LEDs. Diodes have square-law characteristics and thus cause wave forms with high harmonic distortion. When broadband techniques are implemented, the transmitter output excursions must be small to prevent these harmonics. Chapter 4 gives more comprehensive coverage of this material.

Telephone companies are beginning pilot installations with fiber optic trunk lines. These are monomode installations due to the large bandwidths required. Serving commercial customers with fiber optic links are such countries as Japan, the United States, England, and West Germany.

Figure 1–1 is an example of a fiber optic CATV drop with a common coaxial trunk cable. The vampire clamp is easily removed or installed. It has interface circuitry to convert electrical signals to optical. A fiber optic tap is more costly than an electrical tap due to the interface circuitry. The cost of fiber optic cable is gradually dropping, and the situation may improve in favor of fiber optic subscriber drops in the near future.

A star-connected LANs network is shown in Figure 1–2. This is a typical application of fiber optics. In the star-connected system, transmitted signals are broadcast to all receivers. The star network with its multiple receiving stations and high insertion loss requires laser transmitter sources. Lasers produce the necessary power output to overcome the losses.

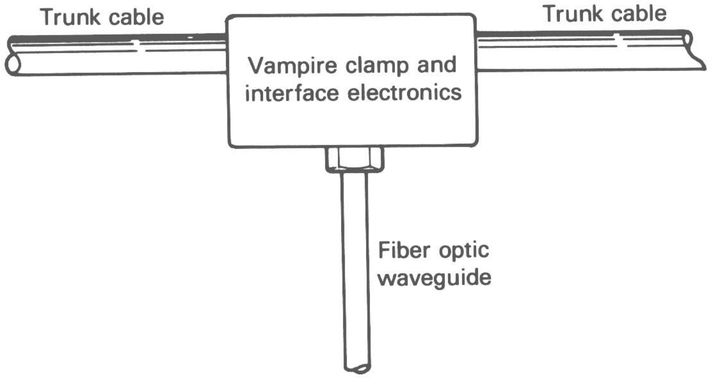

FIGURE 1–1 Fiber optic cable drop.

Low-cost undirectional serial data links (simplex) are popular for LANs applications. Figure 1–3 is a block diagram of a simplex link. The input signal can be either analog or digital, depending on the application and the driving circuitry. Lasers are the sources that convert the electrical signals to optical, while LEDs can perform the same conversion in lower-cost systems. Lasers are implemented in long-distance transmission, and LEDs perform well for short-range use (less than 10 km). Generally, lasers have much more complex driving circuitry, which accounts for some of the increased cost.

Detection is accomplished with solid-state diodes or phototransistors. The two most popular detection devices are the APD and PIN diodes. These are discussed in detail in Chapter 5. Manufacturers have

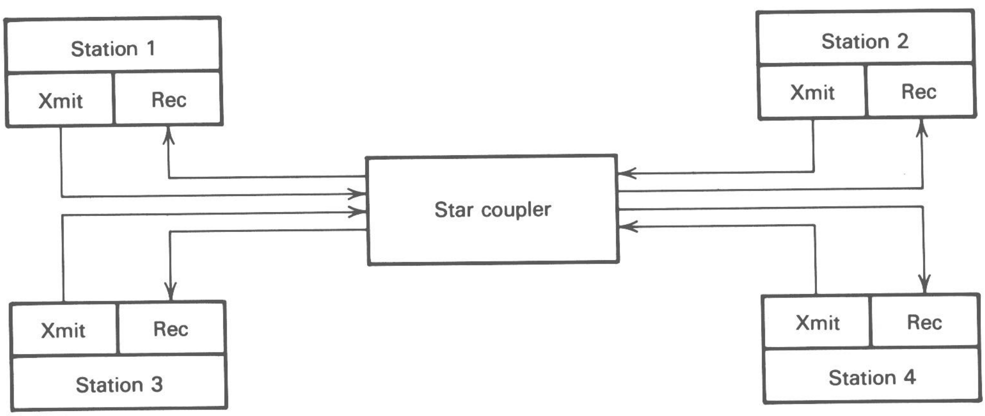

FIGURE 1–2 Star local area network with coupler.